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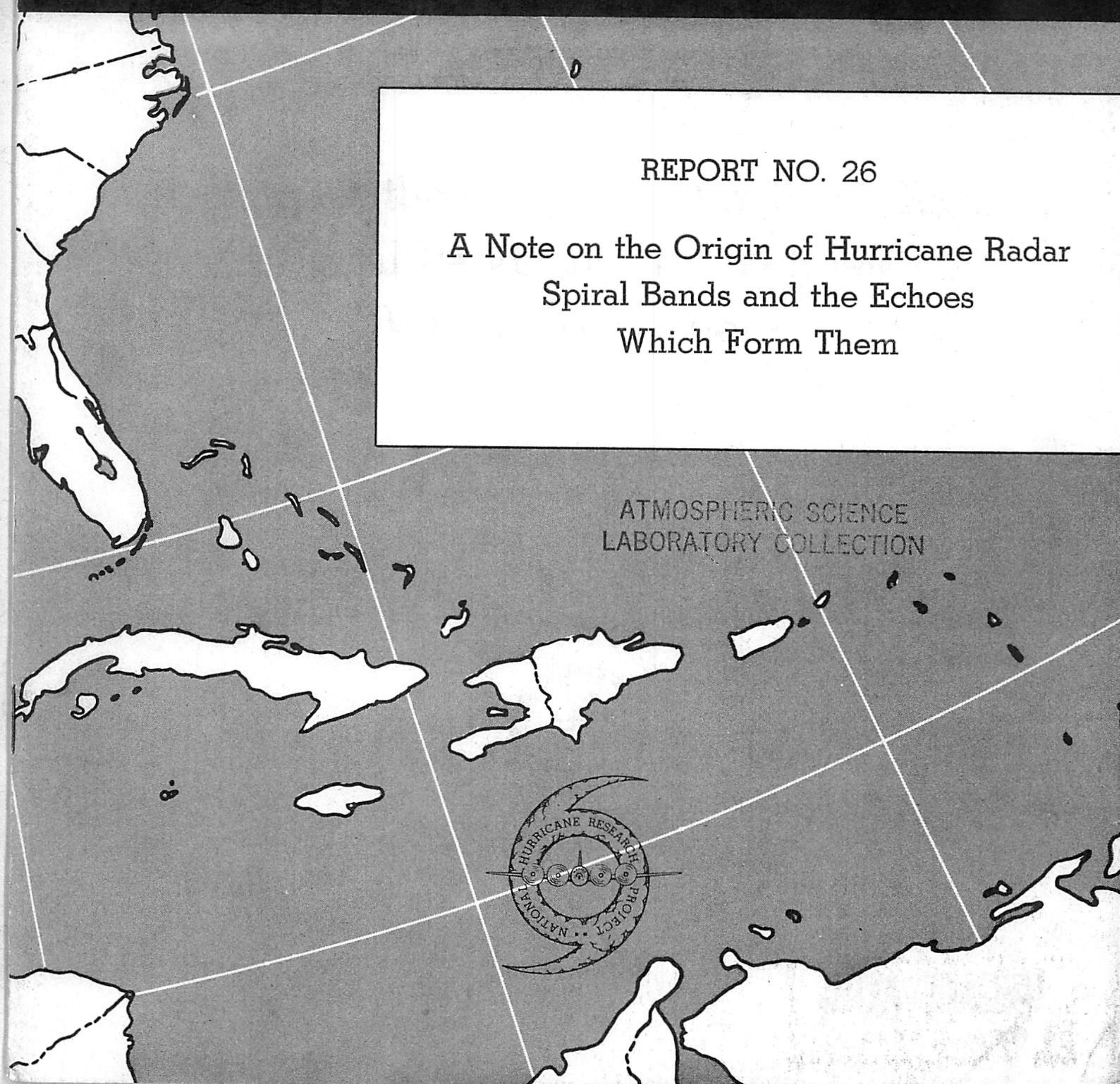

REPORT NO. 26

A Note on the Origin of Hurricane Radar Spiral Bands and the Echoes Which Form Them

U. S. DEPARTMENT OF COMMERCE
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A Note on the Origin of Hurricane Radar Spiral Bands and the Echoes Which Form Them

by
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NATIONAL HURRICANE RESEARCH PROJECT REPORT

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ABSTRACT

Analysis of the histories of spiral rain bands as observed on radar indicates that they are usually formed near the center of the storm and propagate radially outward. The rainband, therefore, maintains a quasi-conservative position relative to the quadrants in which it is formed and does not rotate about the storm center. Furthermore, the radar echoes are not simply pre-existing elements which assume the spiral shape but appear to have their origin in the outward propagated band. Data from several hurricanes are used to illustrate this hypothesis. Evidence is also presented which indicates that the eye of the hurricane is defined by a wall cloud made up of one or more spiral band fragments in the process of generation.

1. INTRODUCTION

Analysis Problems--The study of the origin of hurricane spiral bands is difficult, because good, instantaneous cross sections of these storms are rare; time series of cross sectional data are non-existent. Presently, radar is the only good source of continuous, simultaneous data for several quadrants of a hurricane.

The information portrayed on the radar scope is subject to many uncertainties in interpretation. It is important to note that echoes which appear at various ranges from a land based radar are being observed at widely varying heights, and, depending on the characteristics of the radar, may or may not be "filling the beam," therefore indicating variations in echo intensity which may be completely misleading. The other radar characteristics of wavelength, pulse length, peak power transmitted, minimum detectable signal, dynamic range of receiving equipment, and antenna parameters all affect the characteristics and amount of the echo, and therefore the spiral band, which is seen in both the horizontal and vertical planes.

It is usually necessary, therefore, to make some assumptions about the radar and the way it was operated when the hurricane photographs were taken. Some of these assumptions are reasonably valid; others are less certain but are made in order to arrive at estimates of the true conditions.

With all of the uncertainty in the above variables, the more important aspects of the evolution and movement of precipitation echoes can rarely be seen by two or more radars having different design or even operational characteristics and compared with any degree of accuracy. Many questions concerning the hurricane's weather cannot be answered from analysis of one radar because of the short length of time a given radar has a storm under surveillance, as well as the sometimes limited area which is seen due to the storm's position with respect to the radar. This is especially true for the determination of how much weather exists in a given band or quadrant at extended ranges.

Comparison of weather seen on various land based radars is sometimes difficult [1]; but comparison of the same weather as seen by an airborne and a land based radar may be almost impossible. Aside from the difficulty of differentiating between the weather and surface clutter which usually appears on airborne radarscopes, the aircraft is observing the storm from a height, and through a path which is entirely different from the surface radar. Usually neither the aircraft altitude nor antenna elevation is provided the analyst who studies the film. Under these conditions the same weather would often be seen very differently by land and airborne radars.

A further disparity exists between the weather seen visually from aircraft and what the various radars may "see." During a flight into hurricane Daisy, August 1958, one of the authors noted large portions of the wall cloud and other spiral bands on radar which could not be visually located, even when the aircraft passed through the area of radar return. On another occasion, R. H. Simpson [2] observed radar return in the form of bands in comparatively clear air in a hurricane. In that case, instruments carried by the aircraft showed that a high concentration of water vapor was present, but no visible cloud. It is evident that the sources of data must be carefully considered before intelligent evaluation can proceed.

A micro-scale comparison of radar and synoptic meteorological parameters is extremely difficult because of the unsuitability of the synoptic networks. However, it is becoming generally recognized that, despite small variations in center positions as determined by meteorological parameters of pressure, wind, etc., and the radar eye, the geometric center of the radar eye is probably the best estimate of the storm center for hurricane tracking purposes. Radar data are also useful in studying precipitation elements and their behavior. Although simultaneous synoptic data are not always available, leading to great difficulties in quantitatively determining some of the characteristics of radar echoes, their existence and behavior provide data which can lead to worthwhile conclusions concerning the dynamics of hurricanes.

Hurricane Radar Weather Model--Radar films of many hurricanes which have been studied during the past two years of work on spiral bands have revealed the sequence of hurricane radar weather which is illustrated by the excellent airborne radar photograph in figure 1. All storms have individual differences, and some storms may lack one or more of the well defined features shown in the radar scope photograph from Helene, 1958. However, a "normal" weather sequence might be described as follows:

> The first echoes as seen by a radar well in advance of the storm center are sharply defined and form narrow "pre-hurricane squall lines" [3]. In some storms these squall lines are far enough away from the

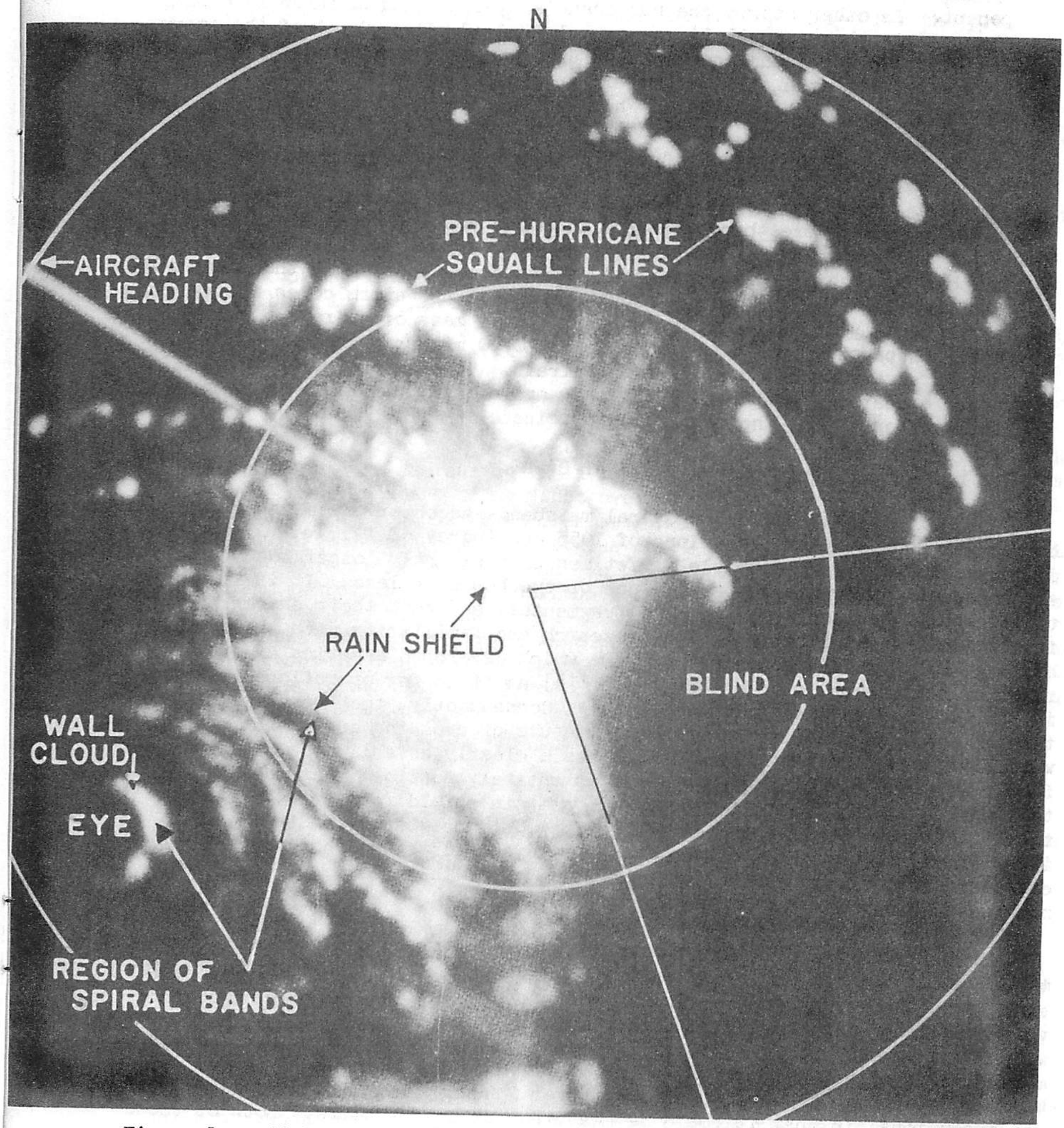

Figure 1. - Airborne radarscope photograph of hurricane Daisy, 1946 GMT, Aug. 27, 1958. Circles are 50 miles apart.

storm center so that the tangential motion of the storm, as indicated by the echoes within the lines, is small compared with the radial component. In other storms the hurricane's cyclonic circulation is easily observed in these squall lines several hundred miles ahead of the storm center. Pre-hurricane squall lines are generally separated by 50 or more miles from the first echoes in a ragged mass of spiraling weather, or there may also be scattered "hard-core" echoes which slowly merge, in a disorganized fashion, into the shield of lighter precipitation. As the hurricane moves closer and the pre-hurricane squall lines have passed the station, the mass of weather ahead of the storm, when examined more closely, is seen to be composed of many spiral bands which apparently merged as they were thrown outward from the center of the storm becoming wider and longer and less well-defined in the process. The leading edge of this rain shield has occasionally been observed to have the shape of a well-defined spiral band. As the center of the storm comes into view, it is usually not directly connected to this mass of spiraling weather, but is separated from it by a space of 10-50 miles which is occupied by one or several much more discrete spirals. The spirals nearest the storm center are most clearly defined and continuous, and it is these which often define the eye of the hurricane.

2. SPIRAL BANDS

Band Lifetime--Analysis of spiral rainbands as observed on radar during hurricanes Connie, Diane, and Ione of 1955 and Audrey of 1957 reveals that individual bands have "measurable" lifetimes only slightly longer than the larger echoes which form them, usually one or two hours or less. It is important to note that the bands are normally fragmentary and that their shapes become increasingly significant only with research and familiarity with them. This has been as true for the research teams which developed a series of overlays relating that shape to the storm center [4] as it is for operational people in the field attempting to use them [5]. Consequently, the "measurable" lifetime of a spiral band means that some measure of crossing angle can be made; which, in turn, implies that the band has a clearly established identity apart from other features of the storm. It is entirely possible that the head and tail of a band may protrude from the large rain shield for hours, extending the life history of the band several times; but uncertainty as to the true identity of the head and tail in this "graveyard" of spiral bands usually exists in such cases, so that for the purposes of this research, the band is not measurable.

Very few bands (frequently only one) from a given hurricane were found to be measurable for periods exceeding 20 to 30 minutes, for many of the reasons listed above. This was surprising in light of the impression that the volume of radar data having well identifiable bands is great. Only five bands were found in the storms studied which could be consistently recognized and measured for over 20 minutes. Two of the five lasted an hour or less. One band in Connie, 1955, was measured for over 2 hours, and one from Diane, 1955, was exceptional in that it could be measured for over 4 hours. Both of these bands were studied extensively.

Band Movement--The photographs in figure 2 from hurricane Diane, taken on the U. S. Weather Bureau radar at Hatteras in August 1955 illustrate the history of a well-formed spiral band from its inception to the time it became an indistinguishable part of the mass of weather. They also indicate the sequence of hurricane weather normally seen on radar, except for the pre-hurricane squall lines which in this case were too far away for the radar to see.

In photograph number 1, at 0605 EST, hurricane Diane was moving NNW at 9 knots, decelerating slowly, had a fairly diffuse eye (which could be accurately determined from later analysis of time-lapse film), and was filling slowly with a central pressure of approximately 987 mb. The arrows indicate the spiral band which is just beginning near the storm center. Total range of the scope is 200 nautical miles and the range markers are at 50-mile intervals.

Photographs number 2 and 3, taken at approximately 1-hour intervals, show the band in its more mature stage as it moves across the space between the storm center and the mass of weather. Photograph number 3 also shows the inception of another band which is becoming identifiable at the right front edge of the eye.

The question arises in photograph number 3 as to whether the radar is overshooting either end of the mature band under study. It is improbable that the echoes found at decreasing radii are lower than those found farther from the storm center and are being "shot over" by the radar beam. It seems probable, therefore, that no weather exists inside of the presently visible "head" end of the band (end nearest the storm center), because weather which exists in other bands to the north can be seen at least 20 miles farther from the radar, indicating that conditions for propagation and detection are probably normal. The "tail" end of the band (end farthest from the storm center) establishes the extent to which weather can be seen in the south quadrant, so no comparisons with other detectable precipitation can be made. However, later photographs indicate there was little or no extra length at the tail end of the band. Therefore, all of the precipitation band is probably being observed in this photograph.

Photograph number 4 apparently also shows the entire linear extent of the band, as well as the fact that it is merging with the mass of weather. However, interpretation from the original film shows that the mature band is still separated from the mass of weather but the "bloom" from the ground return as well as nearby precipitation made photography difficult.

In photograph number 5 at 1004 EST the band can still be identified, although it is much wider and is finally merging with the mass of weather. Note that the other band which formed later is also maintaining its quadrant of origin as it moves outward from the storm center.

In photograph number 6, taken an hour later, both bands have broken up or merged into the mass, losing most of their identities. However, careful analysis of the time lapse film permits the identity of some of the heads and tails of bands for several more hours, even though the major portions of the bands can no longer be identified or measured in terms of crossing angles.

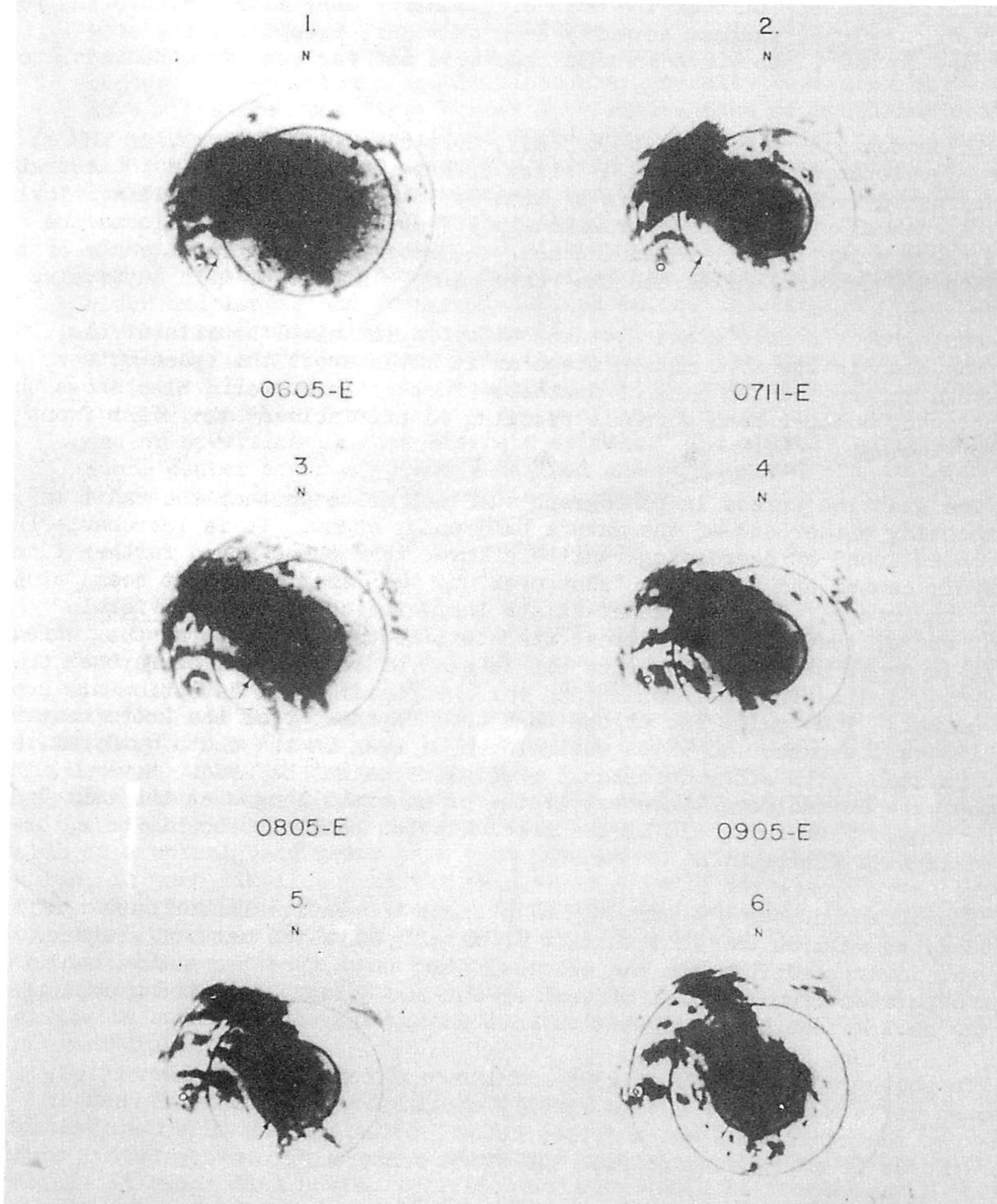

Figure 2. - Hurricane Diane, 0605-1105 EST, Aug. 17, 1955 as seen on U. S. Weather Bureau SP-1 radar at Hatteras, N. C. 50-n.mi. range circles.

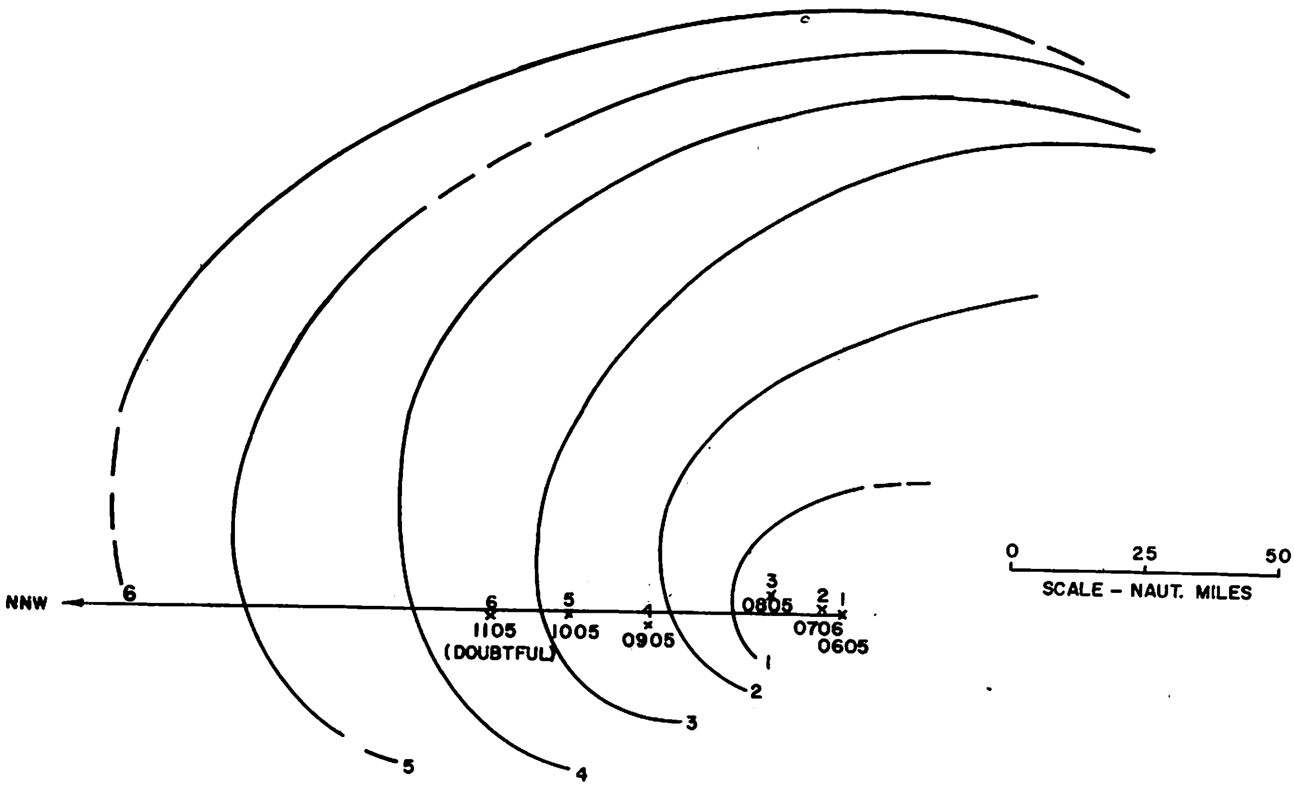

Figure 3. - Hourly band positions relative to a moving center, Diane, 0605-1105 EST, Aug. 17, 1955.

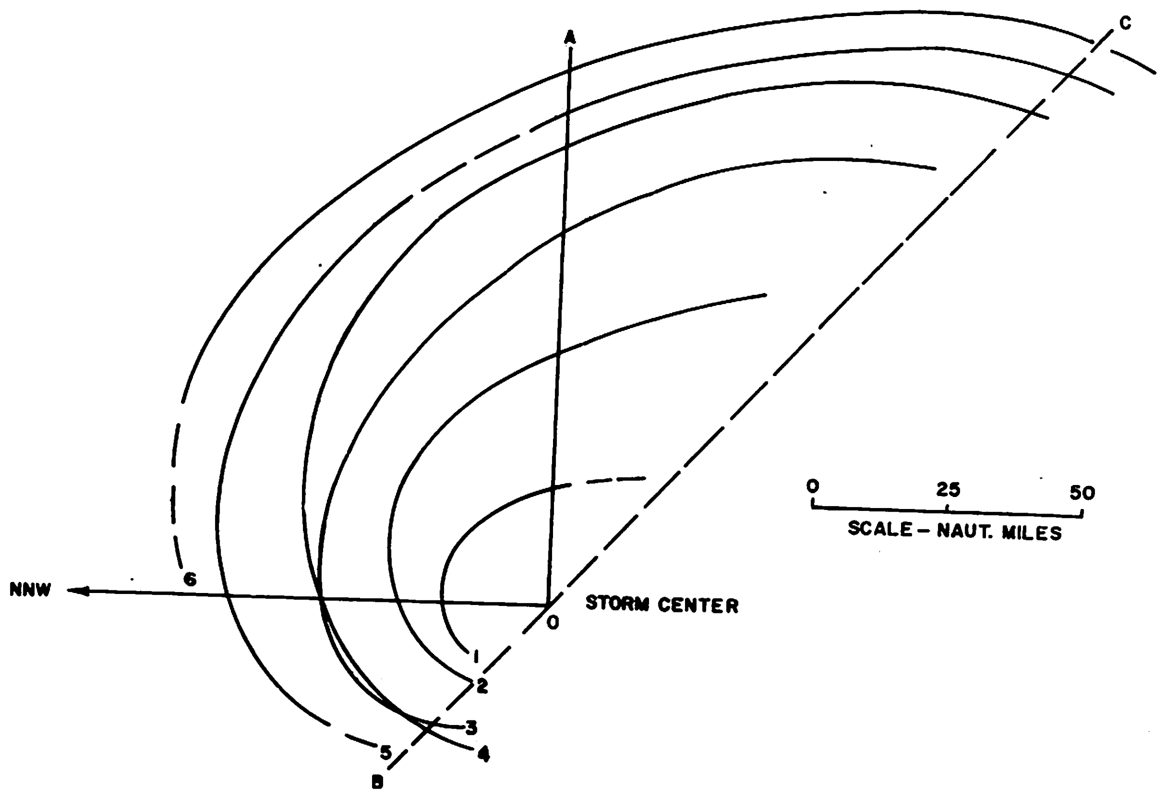

Figure 4. - Hourly band positions relative to a stationary center, Diane, 0605-1105 EST, Aug. 17, 1955.

Figure 3 illustrates the hourly spiral band positions relative to the moving storm center. Although the radar center of the storm appears to move in somewhat erratic fashion, the spiral band moves in a much more consistent manner until parts of it are almost 150 miles from the center. Then the tail of the band slows in its movement away from the storm center and the head starts either to dissipate and break up, or to be "shot over" by the radar.

Figure 4 illustrates the hourly positions of the same spiral band relative to a stationary storm center. The apparent retrogression of the head end between 0805 EST and 0905 EST is due only to the movement of the center, as comparison with figure 2 shows. However, it is important to note that the band did not rotate about the storm but remained in the same relative quadrants from its inception until it became too obscure to be measured. It moved outward from the storm center at 10 knots along the storm path NNW and at over 16 knots along OA normal to the path on the right side of the storm. The outward propagation of the head end in the left front quadrant was slowest, under 6 knots; and that of the tail end in the right rear quadrant was greatest, near 30 knots. The center moved at an average speed of 12 knots during this period.

If figure 4 is redrawn using a 5-hour mean storm speed to arrive at the hourly storm center and relative band positions, the outward movement of the band along ONNW is still somewhat erratic. Instead of positions 3 and 4 coinciding, positions 1 and 2 coincide in this quadrant, with little change in general spacing of other band positions in this and other quadrants. No matter which method of positioning the band with respect to a stationary storm center is used, indications are that some non-uniformity exists in the outward radial speed of the band.

It should be emphasized that this band was the most prominent and lasting single feature of the radar scope while Diane was under surveillance of the Hatteras radar. Although its history was abnormally long and clear, its other features were illustrative of other bands in other storms.

Figures 5 and 6 illustrate a case of outward growth of bands in hurricane Connie as seen on the Hatteras radar on August 12, 1955. In this case the range to all of the elements is such that all important parts of the band are definitely being seen by the radar, attenuation due to intervening precipitation being negligible at the 10-cm. wavelength of the Hatteras radar.

The heads of only the first and last positions are given in figure 6 because the others tend to confuse the picture rather than to clarify it. It is evident that in this case the portion of the band nearest the eye in the left front, right front, and right rear quadrants is either in the formative stages at the outer edge of the eye or is actually a part of the wall cloud which defines the eye. The sequence of head positions given in figure 5 does illustrate that the point of band inception rotates cyclonically about the storm center. However, just as in the case of Diane (figs. 3 and 4) the rest of the band, including the rather certain tail positions, maintains a constant azimuthal relationship to the vector representing storm center motion.

The outward propagation of the band in figure 6 is at the average rate of 4 to 5 knots in all quadrants except those right quadrants nearest the

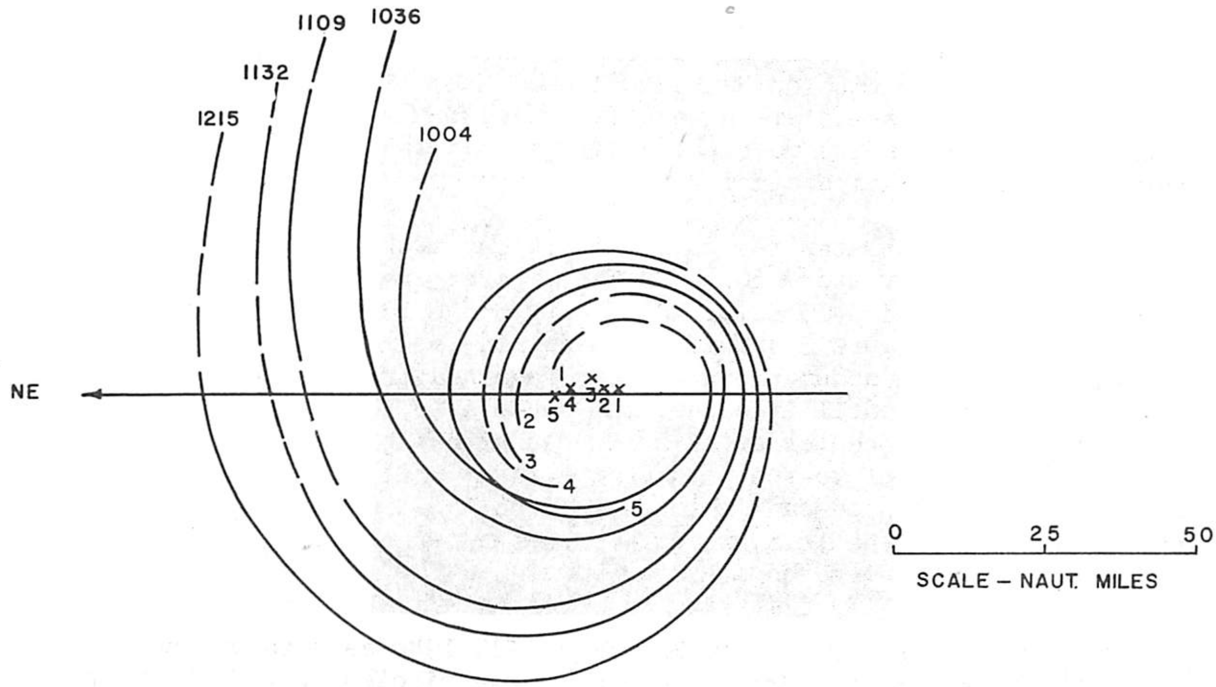

Figure 5. - Half-hourly band positions relative to a moving center, Connie, 1004-1215 EST, Aug. 12, 1955.

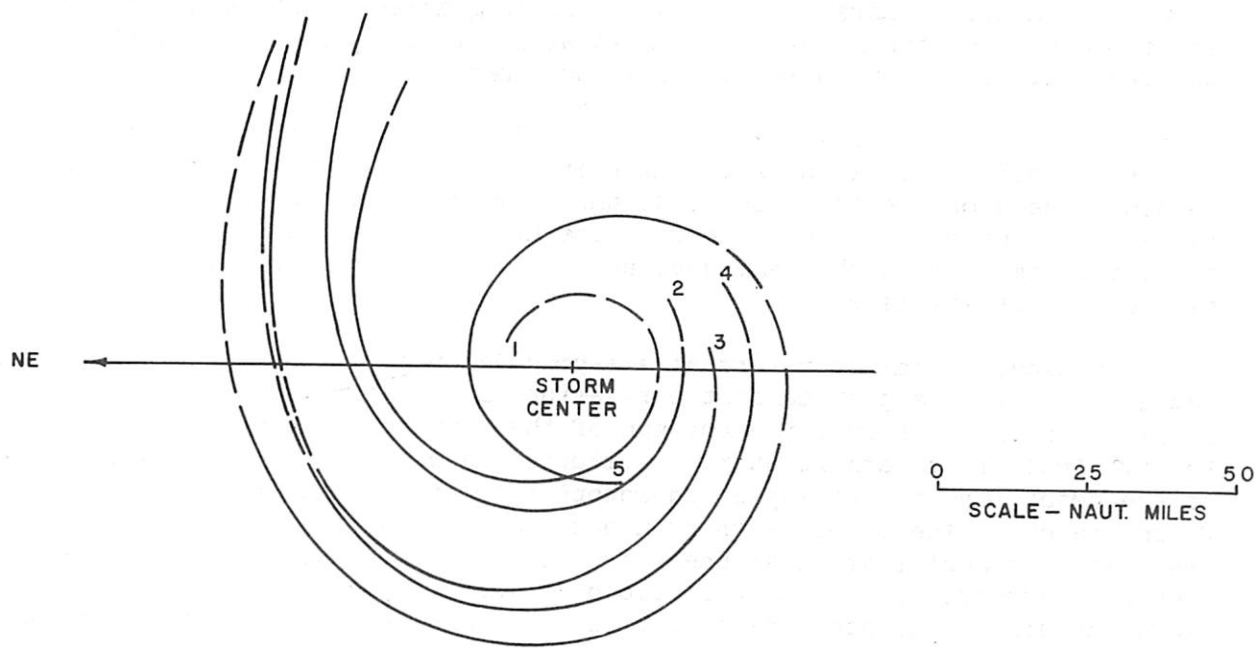

Figure 6. - Half-hourly band positions relative to a stationary center, Connie, 1004-1215 EST, Aug. 12, 1955.

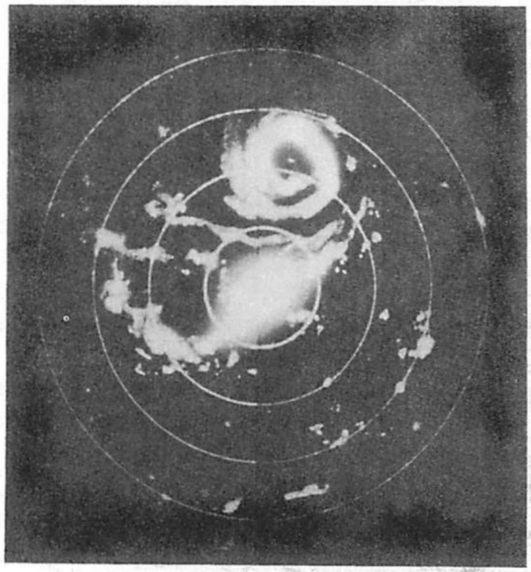

Figure 7. - Hurricane Easy, 1600 EST, Sept. 21, 1948 as seen by radar at Key West Naval Air Station. 20-n.mi. range circles. (U. S. Navy photo.)

storm center, from which several positions were omitted because the band was still definitely in the production stage. This propagation, illustrated in figure 5, does not appear to be at quite as smooth a rate as the example from Diane; and when the motion of the storm center is subtracted, (fig. 6) the rate becomes slightly more erratic in the front quadrants. Redrawing figure 6 using a 5-hour mean storm center speed to arrive at relative band positions does little to smooth the outward radial band motion.

It is evident in these two cases, as well as in others studied, that the spiral bands did not move inward, remain stationary, or rotate counterclockwise about the storm center. Instead, they were produced near the ring of maximum convergence close to the eye of the hurricane, moved outward from the center, and remained in the same quadrants in which they formed throughout their observable lifetimes.

The discovery that spiral bands are produced near the center of the storm leads directly to the problem of the relationship between the bands and the wall cloud which actually forms the eye of the hurricane. Although it is often difficult to determine what constitutes the wall cloud or the eye of the storm, examination of time lapse radarscope film of hurricanes Connie, Diane, and Ione taken on the U. S. Weather Bureau radar at Cape Hatteras in 1955 shows that in almost every case where the eye is well defined (not necessarily shaped symmetrically), the wall cloud is made up of one or more spiral bands which are in the generative process. In some cases where the eye of the storm passed very near the radar, such as at Boca Chica in 1948, even individual photographs show that the wall cloud is no separate entity, but consists of the very early stages of one or more spiral bands. Figure 7 illustrates this clearly.

Before attempting further conclusions regarding the evolution and motion of the bands, it is necessary to observe the characteristics of the echoes which make up the bands.

Echo Life--Previous studies have established the life history of small, discrete rain cells as being of the order of 20 minutes or so [6,7]. However, intermediate and large sized echoes have considerably longer lifetimes, due possibly to some such "bubble theory" of cumulus growth as proposed by Ludlam and Scorer [8], where the cloud family grows in successive stages and in different quadrants rather than as a single convective bubble which forms a cumulonimbus and then rapidly fades away. The intermediate and larger sized echoes are probably far more important to the spiral band than are the very small cells, but the large echoes are difficult to track accurately. The intermediate sized echoes permit tracking for the longest period of time consistent with reasonably small tracking errors. Only those echoes which could be accurately located for 15 minutes or more have been used in this work. An average echo lifetime of the order of about 35 minutes is indicated for them by the present studies.

Echo Movement--Studies are only beginning on the actual movement of echoes that are well within the storm circulation. Table 1 presents the preliminary results of tabulations of echo speed and "crossing angle" by quadrants

Table 1. - Speed and crossing angle versus range from storm center for radar echoes in various storm quadrants.

		Distance from storm center (N. Mi.)					
	Quad.	< 50	51-100	101-150	151-200	> 200	Mean
RF	S	42	74	69	51	35	54
	X_e	10°	4°	12°	7°	13°	10°
	N	1	6	16	13	32	68
RR	S	69	55	14	40	30	42
	X_e	13°	12°	12°	1°	6°	8°
	N	4	6	10	4	15	39
LR	S	62	108	-	-	-	85
	X_e	0°	13°	-	-	-	7°
	N	3	3	0	0	0	6
LF	S	66	57	43	38	25	46
	X_e	38°	5°	- 1°	- 9°	-23°	2°
	N	2	2	10	30	116	160
MEAN	S	60	73	42	43	30	50
	X_e	15°	8°	3°	0°	- 1°	6°
	N	10	17	36	47	163	273

S = Speed X_e = Echo N = Number of observations with respect to storm motion, and by distance from storm center in 50-mile increments for a total of 273 echoes. These data were computed from tracings of echoes at 5-minute intervals from three storms to obtain the velocity vector for each echo. The storm motion was vectorially subtracted from the total echo motion to obtain the echo speed in relation to a stationary storm center. Echo "crossing angle" was then found by measuring the angle between the tangent to the circle whose radius is the distance from the echo to the storm center, and the vector representing echo motion in relation to a stationary storm center. If the vector direction is inward across the circle, the angle is positive, in the same manner as spiral band crossing angles are measured.

Although the echo motion which is referred to in table 1 includes data at most ranges from the storm center out to 250 miles, the spiral band motion studies have been confined to the area of discrete spirals between the wall cloud and the mass of weather.

There are many errors inherent in establishing the precise position and movement of the storm center as well as of individual radar echoes from projected film. Most of these errors should be random in nature, becoming less important as the sample in a given class becomes larger. The results in table 1 appear to corroborate this, since the reliability of a given figure seems roughly proportional to the number of observations, N. As more data are added to the table, the results should become more conclusive.

Echo and Band Motion Together--When echo motion is studied by means of time lapse radar photographs viewed as a movie, first impressions are that echoes move cyclonically down the spiral bands toward the storm center, in conformity with the inward spiraling low-level wind field as shown in previous studies [4]. It is also a recognized fact that the low-level wind field is primarily responsible for the advection of most of the energy toward the storm center [9]. Several investigators have studied the relationship between wind fields and echo velocities in hurricanes. Some have met with apparent success. However, most researchers have considered only advection, ignoring the propagation effects on hurricane radar echoes.

If advection of the echo in the wind field were the only important factor in echo motion - and the spiral band shape is a reasonable approximation of the inflow in the low-level wind field - then figure 8 illustrates the echo movement which might result. Here the storm center is stationary and the spiral band is held fixed in radius and azimuth with respect to the storm center. Then an echo at X_1, radius r_1, would reach X_2 in time t_1, while an echo at A_1, radius r_2, would reach A_2, which is outside the wall cloud, in the same time. Both echoes would then travel a path having a crossing angle of 0° with respect to the spiral band. However, they would travel different distances down-band toward the storm center due to necessary differences in velocity, if they were being simply advected by the low-level wind field. The relation between the velocity V and the radius r at which it is observed is assumed to be of the form

$$V = f\,(1/r) \qquad \text{(Eq. 1)}$$

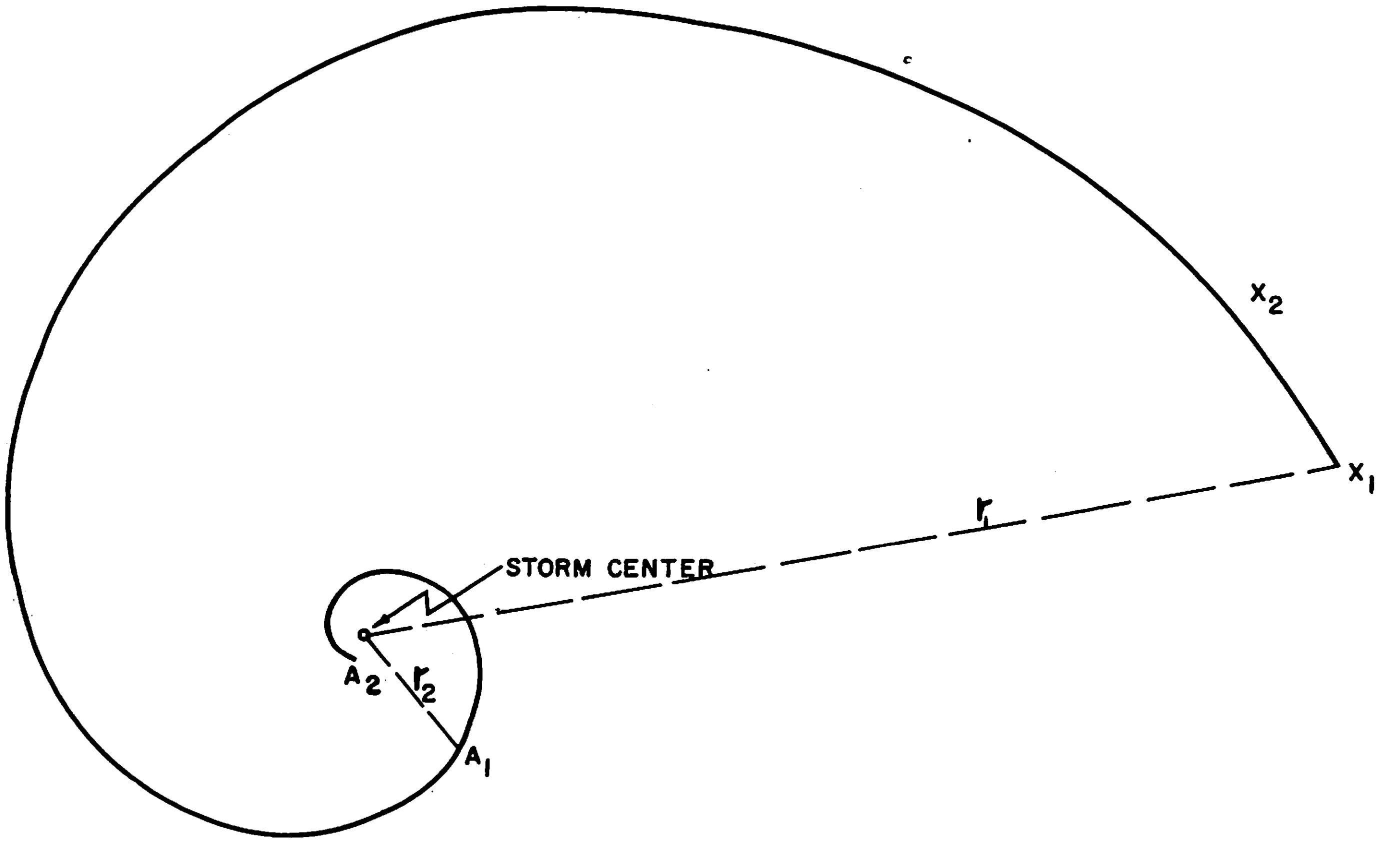

Figure 8. - Echo movement along a stationary spiral.

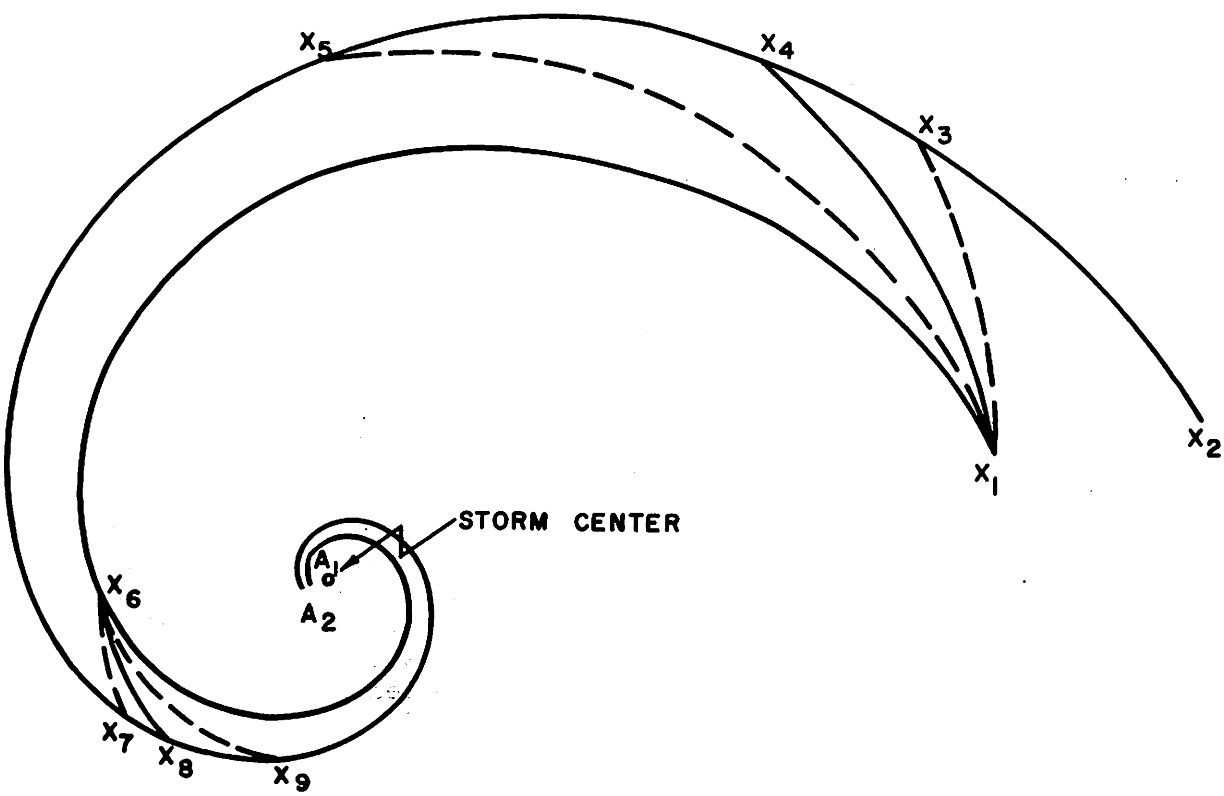

Figure 9. - Echo movement along an outward-expanding spiral.

One consequence of this stationary spiral with respect to the storm center would be a band which would shrink on the outer end and grow on the end near the storm center as a result of advection of echoes which form the band. The spiral would then appear to move inward and rotate cyclonically about the storm center. But this contradicts the data presented in figures 2 through 6, so the band cannot be stationary.

Previous work [3] indicates that the crossing angle of the spiral band changes little with time or radius from the storm center. Therefore, either echo direction, with respect to the spiral band, must vary with distance from the storm center, or if echoes maintain positions within the bands, then the bands must change position with respect to the storm center. See figure 9. Here, the spiral bands X_1A_1 and X_2A_2 have the same 20° crossing angle, and X_1X_5, X_1X_4, and X_1X_3 represent echo paths which cross the stationary spirals at 10°, 20°, (circular arc with respect to storm center), and 30° respectively. Considering equation (1), it can be seen that an echo at X_1, time t_o must take a shorter path (along or outside of X_1X_3) than one at X_6 (which must assume a path well inside of X_6X_9) if they are both to be located on spiral X_2A_2 after time Δt. It is also apparent that the angular velocity about the storm center will be much greater for the echo starting at X_6 than for that at X_1, if time is constant. Although a component of motion across the band seems evident at first, if the movement of the band is subtracted, then at any time between and including t_o and t_1, the echo is within the spiral band and traveling inward toward the storm center.

It should be noted in figure 9 that if band X_1A_1 is simply rotated counterclockwise, it will not completely coincide with band X_2A_2 after time Δt, or with the facts observed in figures 2 through 6, unless some mechanism can be found which generates new echoes between X_2 and X_3 and dissipates them inside of A_2. Otherwise, this rotation of X_1A_1 will result in X_3A_3, where A_3 (not shown) is a point at least 180° to 360° down-spiral toward the storm center.

If the band is therefore not rotating about the storm center, but the radius at which it is found in a given quadrant is steadily increasing, then it must be moving radially outward by some unknown mechanism.

There are two factors which may contribute to the outward motion of bands. One of these is the outward propagation of the individual echoes which form the bands, and the other is the effect of cross band shear of the upper level winds. Propagation, which has not previously been given proper consideration in hurricane echo motion, may prove to be a significant factor in the outward motion of the bands. These effects can only be studied by careful consideration of the wind fields which influence the motion of the echo. Since sufficient simultaneous radar and wind data have not yet become available, it is not possible to determine quantitatively propagation effects.

The nearly circular or even outward flow about the storm center which has been observed in the middle troposphere [10], produces shear forces acting on the tops of the echoes which could account for some of the observed echo motions in table 1 and part of the outward motion of the spiral bands. It seems evident that some propagating mechanism other than the wind field must be present to create new echoes continuously and to provide for the maintenance of the band as it moves outward. Much more complete hurricane data will be necessary before solutions to these problems are possible.

3. CONCLUSIONS

Contrary to common impressions, the present data indicate that spiral bands form near the ring of maximum convergence close to the eye as a result of some phenomena such as gravity waves or the strong vertical upthrust which occurs at the wall cloud. This does not seem to be a uniform circular release of energy there, which would create ever-widening circular bands of weather, but energy which is probably released as it oscillates around the wall cloud of the eye, creating one portion of a spiral band in a given quadrant at a given time and another section of the spiral at a later time in the next counterclockwise quadrant. The result of this time differential in the continuous formation of the band would impart a spiral shape and establish its quadrant with respect to the storm center. This also accounts for irregularities in the shape of the eye which is formed by spiral bands in the generative stages. Both the gravity wave and the hurricane's upper level circular or outward wind field could then provide the mechanism for the outward propagation of the spirals which is observed. Furthermore, the bands usually tend to remain in the same quadrant or quadrants in which they form.

Echo trajectories which are more circular than the spiral bands can be explained by this outward movement of the band. Individual echoes may then be regarded as passively carried downwind, down-spiral, with the spiral precipitation-producing line propagating outward at a rate consistent with the echo velocities. If an exact solution to equation (1) is assumed, it may eventually be possible to express the trajectory of an echo, its crossing angle, and its angular speed of rotation about the storm center at any given radius, in terms of the crossing angle and outward velocity of the spiral band. The evidence in figures 2 through 6 also indicates that there may be a direct relationship between outward spiral band motion and forward motion of the hurricane which may be exploited for further operational use. Future research, directed along these lines, should materially aid in the formulation of a workable mathematical hurricane model.

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